

Thermal Design of an Orbiting Sample (OS) for Martian Orbit

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Outline

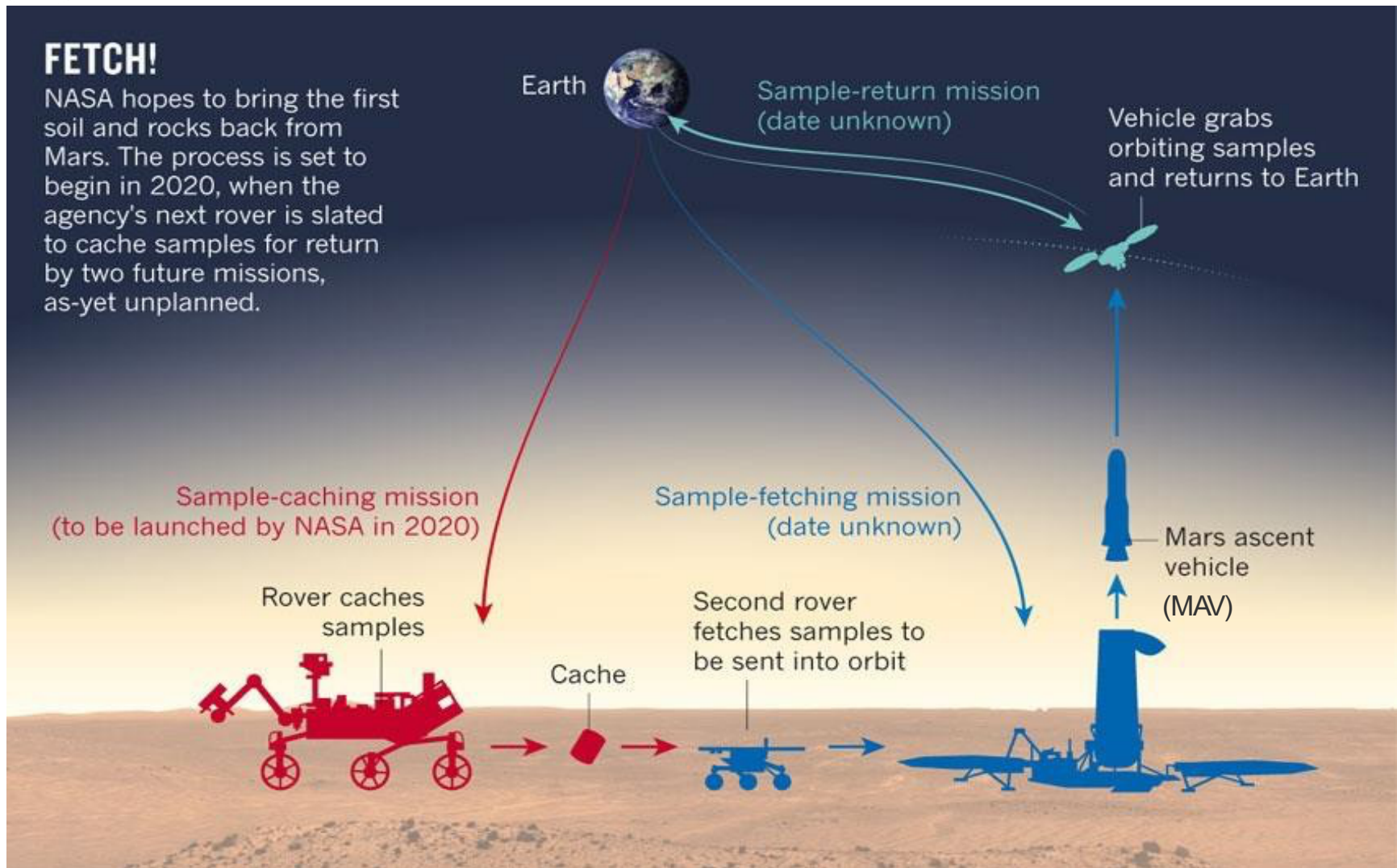
- Introduction
- Key and Driving Requirements
- Temperature Requirements
- OS with Beacon vs. OS without Beacon
- OS Coating Selection and Optical Properties
- WCC and WCH Temperature Predictions
- OS Design Concept
- Conclusions



Potential Mars Sample Return Mission

FETCH!

NASA hopes to bring the first soil and rocks back from Mars. The process is set to begin in 2020, when the agency's next rover is slated to cache samples for return by two future missions, as-yet unplanned.



[1] Reprinted by permission from Macmillan Publishers Ltd: Witze, A., "NASA plans Mars sample-return rover," Nature News, 13 May 2014. Copyright 2014.



Key and Driving OS Requirements

- OS must have mass below 12 Kg [2].
- OS must have diameter below 28 cm.
- OS must survive cold winter soak on the surface of Mars prior to ascent (-80 °C).
- OS must withstand aerothermal heating during MAV ascent.
 - TPS is required due to high heat fluxes ($\sim 12 \text{ W/cm}^2$) [2].
- OS must be able to be captured by return vehicle.
 - OS must have a solar reflectivity > 0.37 [2].
 - This would allow visible tracking in the Martian Orbit.
 - OS must be a diffuse reflector.
 - At long ranges, a specular OS may be “invisible” if the OS is not a perfect sphere.
 - At short ranges, a specular OS could cause glint issues, be difficult to resolve its outline, and determine its range.
- OS must be capable of surviving Earth entry and impact with ground ($\sim 1300 \text{ g}$) [2].

[2] Perino, S., et al., “The Evolution of an Orbiting Sample Container for Potential Mars Sample Return,” IEEE Aerospace Conference, Big Sky, MT, March 4-11, 2017.



Sample Temperature Requirement

- The maximum sample temperature is a science requirement.
 - There is no minimum sample temperature.
 - Mars 2020 has a relaxed sample temperature requirement due to challenges with keeping tubes cool on the surface of Mars at the worst case landing site.
 - It is likely that samples will be kept below 30 °C once a real landing site is selected [3].

Max Sample Temperature	Requirement	Goal
Mars 2020	60 °C	40 °C
Mars Sample Return	30 °C	None

[3] Redmond, M., Sherman, S., Bhandari, P., and Novak, K., "Thermal Design, Analysis, and Sensitivity of a Sample Tube on the Martian Surface," 47th International Conference on Environmental Systems, Charleston, SC, July 16-20th 2017.



Temperature Requirements Table

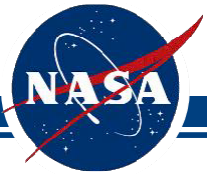
- MAV **AFT (Allowable Flight Temperature)** could be as low as -67 °C, controlled by survival heating.
 - Preliminary Secondary Battery Testing has been done from -60 to +50 °C operational (charging and discharging) and -80 to +50 °C non-operational **using a commercial battery with JPL developed electrolyte.**
 - **Electronics**, like those used on Deep Space 2, are capable of qualification down to **-100 °C.**
- **Sample Tubes** and hermetic seal are qualified down to **-135 °C** [3].
- **Solar Cells** are typically qualified to **150 °C** on the hot side.
- **Al-7075 OS Structure** loses 30% of its strength with < 10 hours of exposure at **150 °C** [4].
 - Parts of OS Structure are predicted to reach 90 °C during MAV ascent.
- Max Continuous Operating Temperature of **Torlon is 260 °C** [5].
 - Portions of the antenna are predicted to reach 150 °C during MAV ascent.

	Non-Op Qual	Non-Op AFT	Op Qual	Op AFT
Battery	-82 to +50 °C	-67 to +30 °C	-60 to +50 °C	-45 to +30 °C
Electronics	-82 to +70 °C	-67 to +50 °C	-60 to +70 °C	-45 to +50 °C
Sample Tubes (Ti-6Al-4V)	-135 to +70 °C	-120 to + 50 °C	-135 to +70 °C	-120 to +50 °C
Solar Cells	-135 to +150 °C	-120 to +130 °C	-135 to +150 °C	-120 to +130 °C
OS Structure (Al-7075)	-135 to +150 °C	-120 to +130 °C	-135 to +150 °C	-120 to +130 °C
OS Antenna (Torlon)	-135 to +250 °C	-120 to +230 °C	-135 to +250 °C	-120 to +230 °C

3Redmond, M., Sherman, S., Bhandari, P., and Novak, K., "Thermal Design, Analysis, and Sensitivity of a Sample Tube on the Martian Surface," 47th International Conference on Environmental Systems, Charleston, SC, July 16-20th 2017.

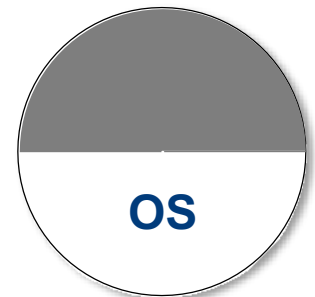
4 Metallic Materials Properties Development and Standardization (MMPDS-05), FAA, April 2010.

[5] "Torlon," WS Hampshire Inc., <http://www.wshampshire.com/pdf/torlong.pdf>



No Beacon OS Design

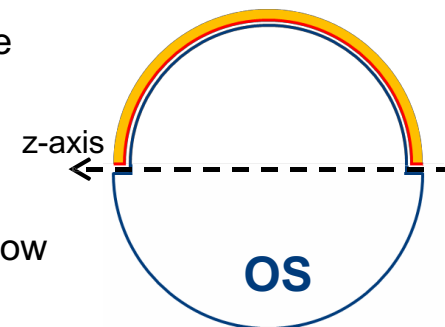
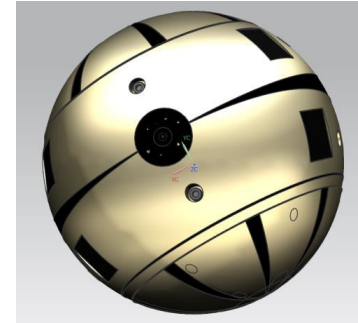
- The OS and collected samples would be **capable of surviving very cold temperatures**.
- If TPS is not on the OS or is ejected, the **entire OS could be painted white** to increase its solar reflectivity.
- If TPS is directly on the OS, the TPS could be black, white, or gray, as long as **one hemisphere of the OS is painted white**.
 - Assuming that the **OS is spinning**.
 - The TPS would still need to meet the **OS manipulation** requirements of the rendezvous operations in Martian orbit.
 - Placing TPS directly on the OS would likely reduce the **OS reflectivity**.
 - **TPS charring** could affect both manipulation and reflectivity.



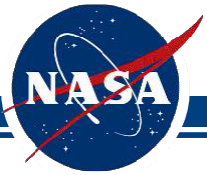


OS Design with Beacon

- The OS and collected samples must be kept between **-45 and +30 °C AFT** (-60 to +50 °C Qual) **for all orbits** using only **passive thermal control**
 - The beacon's battery is the limiting hardware.
 - The maximum sample temperature (+30 °C goal) also is a concern.
- If TPS is not on the OS or is ejected, the OS would be coated in a combination of coatings with **both high reflectivity and high α/ϵ** .
 - The combination that does this best is **Diffuse Gold and Black Paint**.
- If TPS is directly on the OS, the TPS would need to be thermally isolated from the OS, due to high emissivity of TPS.
 - The non-TPS OS hemisphere would be **Diffuse Gold and Black Paint**.
 - Even with thermal isolation, the design would be **less robust** than if the TPS was not on the OS in the first place.
 - Thermal isolation would consume **significant volume**.
 - The OS would need to **spin around z-axis** to ensure thermal control.
 - The TPS and TPS support structure would need to be **RF transparent** to allow the beacon to transmit through it.
 - The TPS would still need to meet the **OS manipulation** requirements of the rendezvous operations in Martian orbit.



Lots of Constraints!



OS with Beacon Coating Selection

- Gold is a good solar reflector, which is needed for visible tracking.
 - Better than Chromium, Steel, Nickel, Titanium, Tungsten, or Copper.
 - Worse than Aluminum and Silver.
- Mars Orbit is Cold!
 - Gold has a high α/ϵ
 - Aluminum and Silver do not.
 - Black paint also has a high α/ϵ
- Both Gold and Black Paint are stable and surface properties should not change over time.
 - The mission duration is up to 10 years in orbit.
- Gold coatings have significant heritage in aerospace applications
 - Diffuse gold coatings are often used in integrating spheres.
- Gold is commonly used for antennas, which is good since the OS with Beacon would need an antenna on its surface.



Potential OS Surface Coatings



1" diffuse gold coupon using Surface Optics' standard process of grit blasting and gold plating



2" x 5" coupon coated with Aeroglaze® Z306 Black Paint



2" diffuse gold coupon using Epner Technology's standard process of 120 grit blasting and laser gold plating

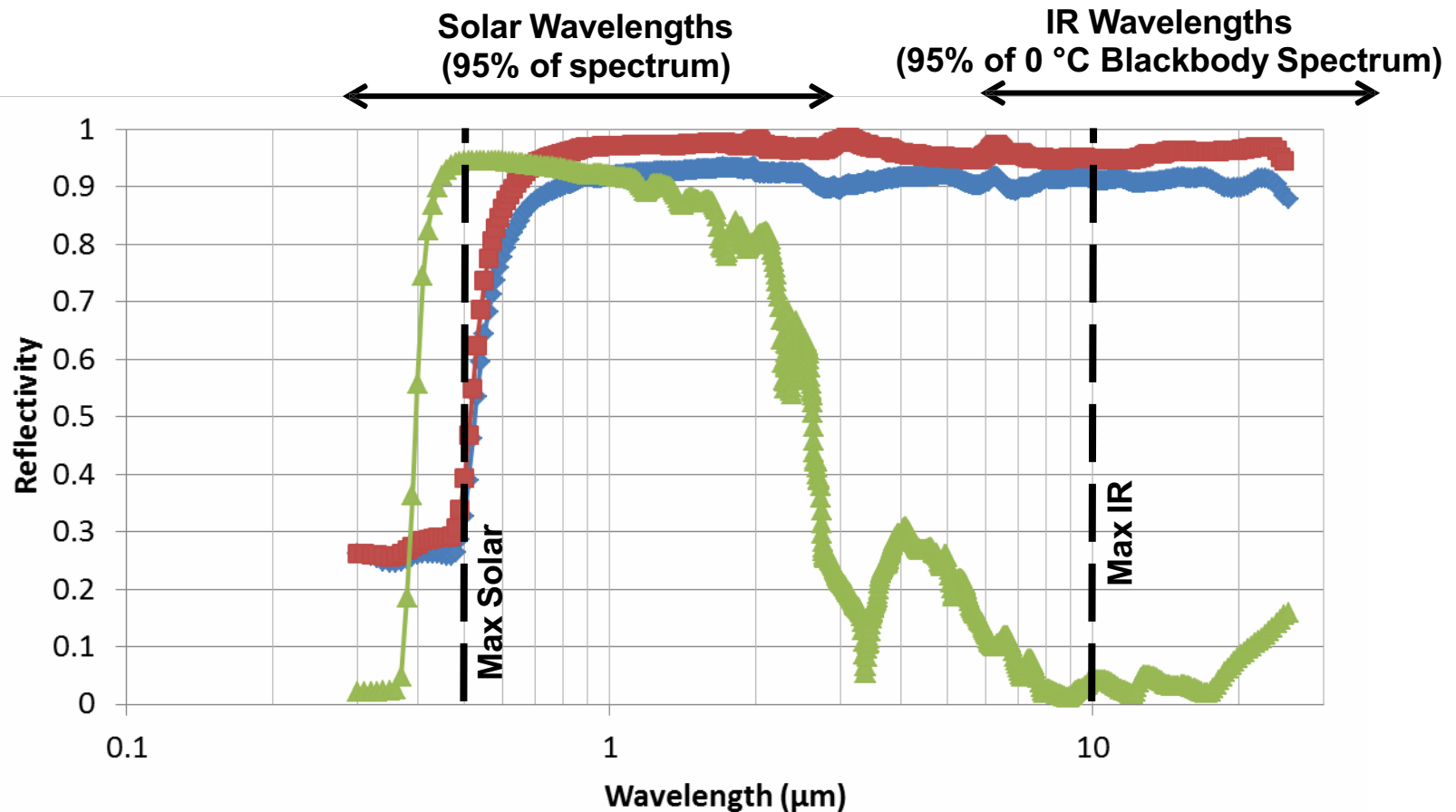


2" x 5" coupon coated with S13GP:6N/LO-1 White Paint



Hemispherical Directional Reflectance

- Reflectance measurements were taken at an incident angle of 8 degrees from normal.

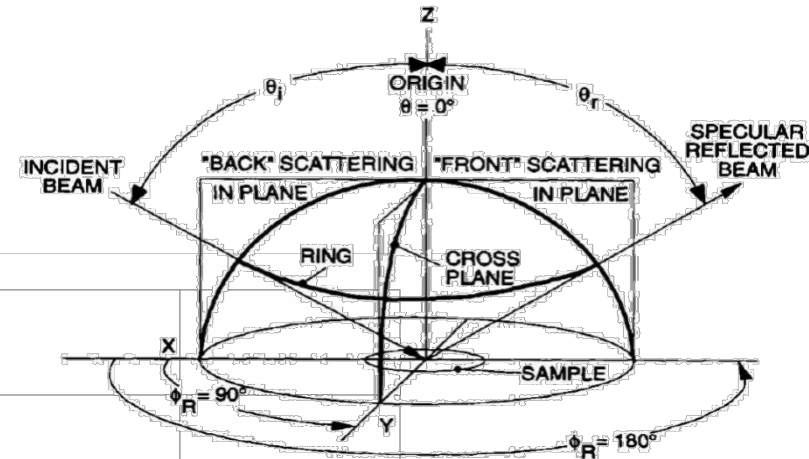
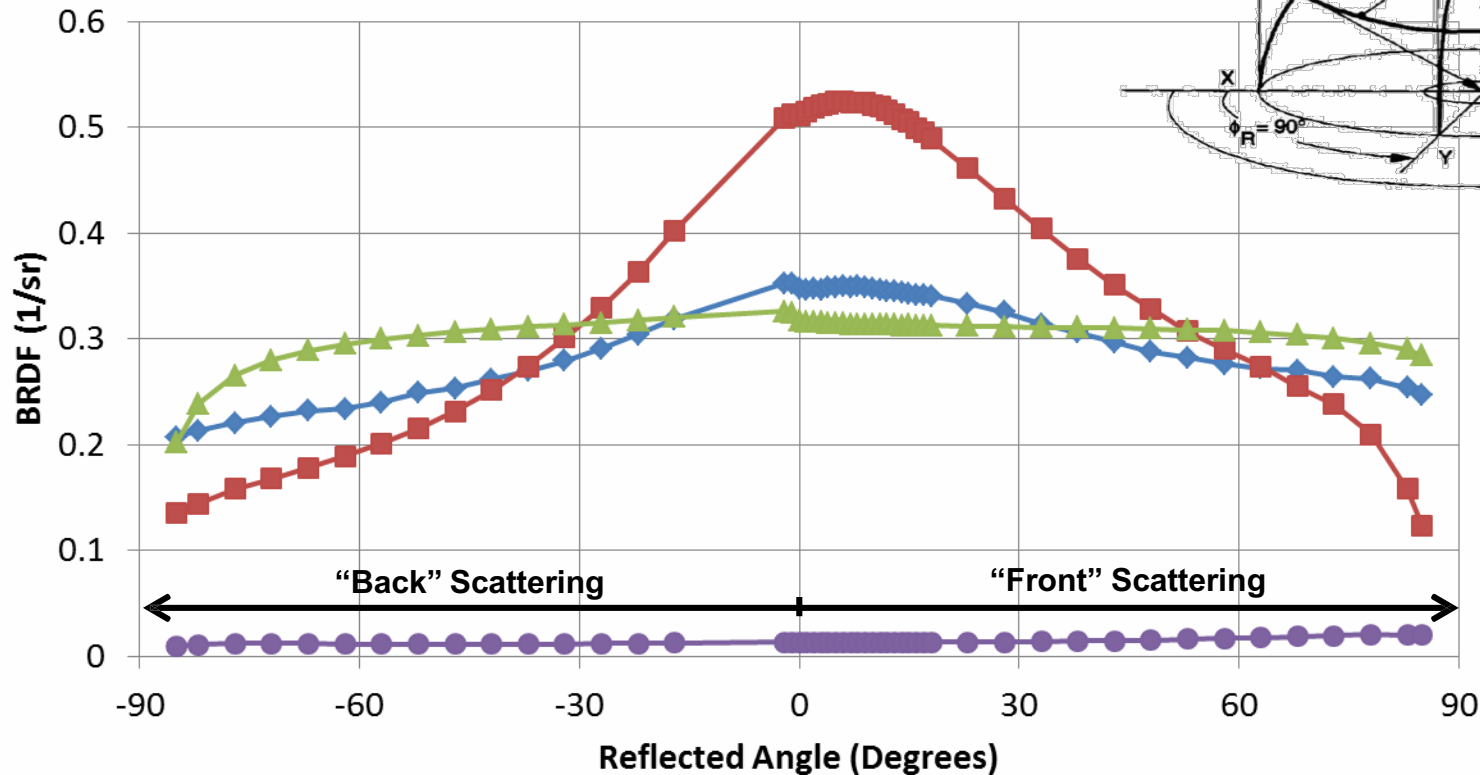


—◆— Diffuse Gold, Surface Optics —■— Diffuse Gold, Epner Technology
—▲— White Paint, S13GP:6N/LO-1



BRDF Measurements

- BRDF measurements:
 - In plane measurements only
 - Using a 643 to 712 nm wavelength filter
 - Taken at 8 degrees from normal incident angle



Materials tested were Mostly Diffuse

- Diffuse Gold, Surface Optics
- Diffuse Gold, Epner Technology
- White Paint, S13GP:6N/LO-1
- Black Paint, Aeroglaze® Z306

Diffuse = "Flat Line"
Specular = "Spike"



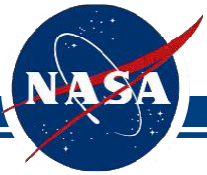
Optical Properties (α and ϵ)

- Optical property (α and ϵ) measurements come from 3 sources:
 - Literature Values (Spacecraft Thermal Control Handbook, [6])
 - Directional Reflectance at 8 degrees from normal measured by Surface Optics
 - Total Hemispherical Reflectance measurements using a TESA 2000 at JPL
 - This data is used to come up with values to be used in thermal analysis
 - Properties assumed to vary by the smaller of +/- 50% or +/-0.05
 - Uncertainty caused by natural variation, measurement error, and contamination.

Surface Coating	Measurement Source	Solar Absorptivity, α	Thermal Emissivity, ϵ
Surface Optics Diffuse Gold	Range with Uncertainty	0.22 to 0.32	0.05 to 0.15
Surface Optics Diffuse Gold	Directional Reflectance, 8°	0.25	0.09
Surface Optics Diffuse Gold	Total Hemispherical	0.29	0.12
Epner Technology Diffuse Gold	Range with Uncertainty	0.18 to 0.28	0.02 to 0.07
Epner Technology Diffuse Gold	Directional Reflectance, 8°	0.22	0.04
Epner Technology Diffuse Gold	Total Hemispherical	0.24	0.05
S13GP:6N/LO-1 White Paint BOL	Range with Uncertainty	0.15 to 0.25	0.85 to 0.95
S13GP:6N/LO-1 White Paint BOL	Literature Value	0.19 to 0.22	0.88 to 0.89
S13GP:6N/LO-1 White Paint BOL	Directional Reflectance, 8°	0.18	0.94
Aeroglaze® Z306 Black Paint	Range with Uncertainty	0.90 to 1.00	0.85 to 0.95
Aeroglaze® Z306 Black Paint	Literature Value	0.95	0.87

[6] Gilmore, D. (ed.), "Spacecraft Thermal Control Handbook," 2nd ed., The Aerospace Corporation, 2002.

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OS Average Orbital Temperature

- Average Temperature of a **Sphere in Orbit Around A Planet** using Energy Balance:

$$T_{OS} \neq f(r)$$

$$T_{OS} = f(\alpha/\epsilon)$$

$$Q_{in} = Q_{out}$$

$$Q_{solar} + IR_{in} + Q_{alb} = IR_{o}$$

$$\pi r^2 \alpha_0 q''_{solar} (1 - f_{eclipse}) + 4\pi r^2 F_{OS-Planet} \epsilon_{OS} \sigma T_{net}^4 + 4\pi r^2 F_{OS-Planet} \alpha_{OS} (1 - \alpha_{Planet}) q''_{solar} (0.25) = 4\pi r^2 \epsilon_{OS} \sigma T^4$$

Assume average planet albedo uses a 0.25 factor since planet cross section is 1/4 of its surface area.

$$f_{eclipse} = \frac{1}{B} \cos^{-1} \frac{h^2 + 2Rh \cos \beta}{R + h} \quad \text{if } \beta < \beta^*$$

$$f_{eclipse} = 0 \quad \text{if } \beta \geq \beta^*$$

$$\beta^* = \sin^{-1} \frac{R}{R + h} \quad 0^\circ \leq \beta^* \leq 90^\circ$$

$$F_{OS-Planet} = \frac{1}{2} \left(1 - \sqrt{1 - \frac{R^2}{D^2}} \right)$$

D = center to center distance from OS to Planet
 $F_{OS-Planet}$ = View Factor from OS to Planet
 h = Orbit altitude
 q'' = Heat flux

r = OS radius
 R = Planet radius
 T = Temperature in Kelvin
 α = Solar absorptivity

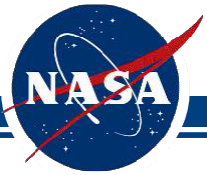
β = Beta angle
 β^* = Beta angle at which eclipses begin
 ϵ = Thermal emissivity
 σ = Stefan-Boltzmann constant

[6] Gilmore, D. (ed.), "Spacecraft Thermal Control Handbook," 2nd ed., The Aerospace Corporation, 2002.
 [7] Howell, J.R., "A catalog of radiation configuration factors", McGraw-Hill, 1982.



OS WCC and WCH

	Worst Case Cold (WCC)	Worst Case Hot (WCH)
Beta Angle	0°	90°
Altitude	400 km	400 km
Solar Flux	493 W/m ²	717 W/m ²
Average Mars Temperature (IR)	-73 °C	-53 °C
Mars Planetary Albedo	0.26	0.26
Biased Optical Properties	High ϵ , Low α	Low ϵ , High α

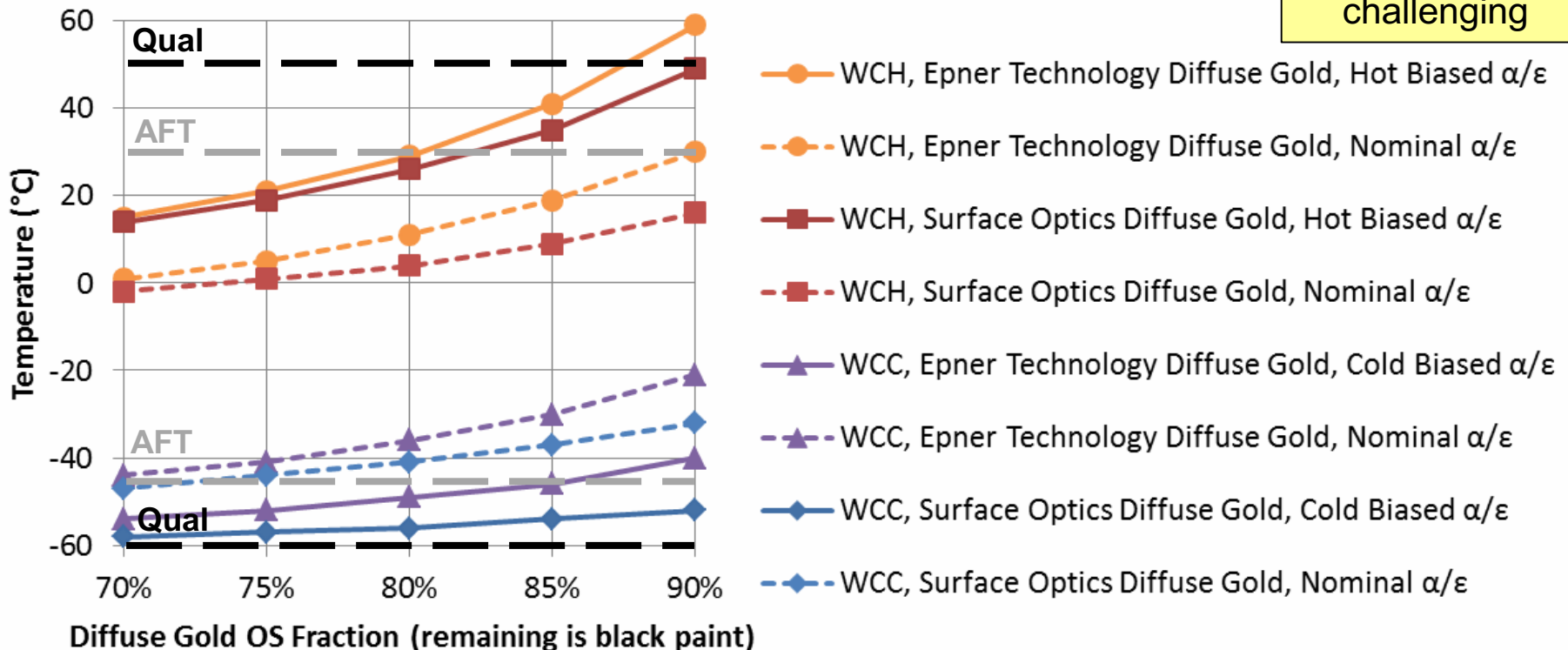


OS Orbital Temperature Predictions

- OS without Beacon :
 - WCC Temperature with 100% White Paint = -111 °C.
 - WCH Temperature with 100% Black Paint = -15 °C.
- OS with Beacon needs a mixture of Black Paint and Diffuse Gold:
 - Assume a mixture of 85% Diffuse Gold, 15 % Black Paint.
 - Stacked Worst Case Predictions are within Qual, but not AFT:

No Beacon OS is very simple thermal design!

OS with Beacon is more challenging





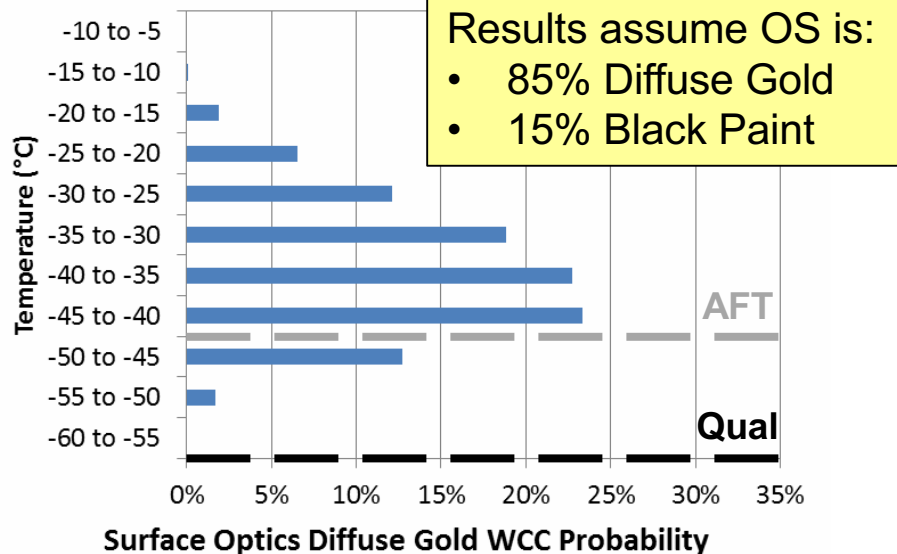
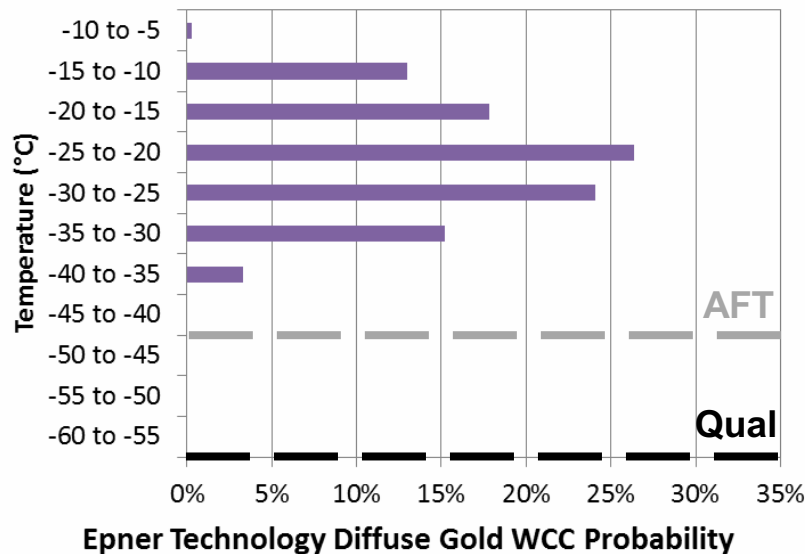
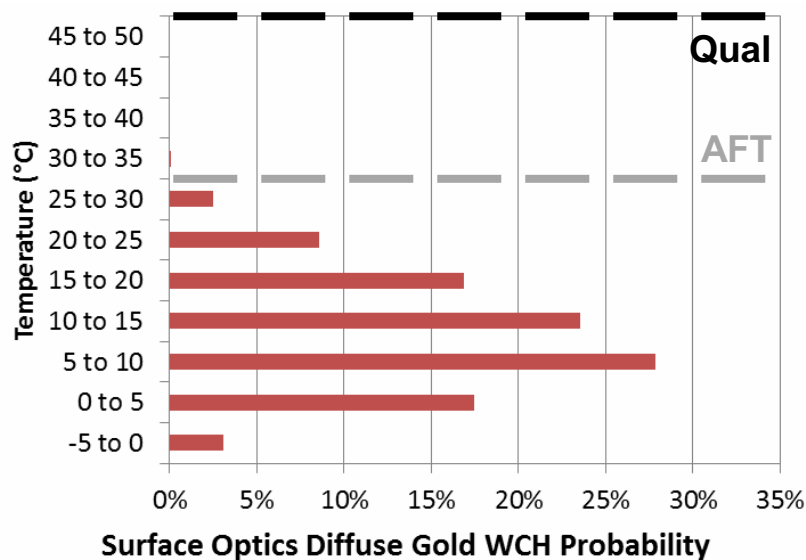
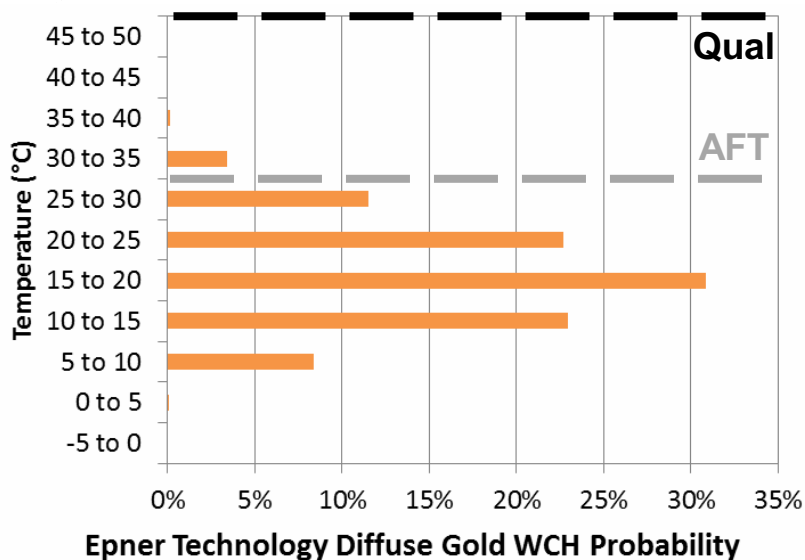
Monte Carlo Temperature Study

- The probability that worst case optical properties occur on diffuse gold and black paint simultaneously is very low.
 - Assume there are 4 independent variables:
 - $\alpha_{\text{BlackPaint}}$, $\epsilon_{\text{BlackPaint}}$, $\alpha_{\text{DiffuseGold}}$, $\epsilon_{\text{DiffuseGold}}$
 - Assume a uniform distribution for each variable.
 - Assume an OS with 85% Diffuse Gold, 15% Black Paint.
 - Perform Monte Carlo Temperature Study with 10,000 combinations.
- Probability of Exceeding Allowable Flight Temperature (AFT) or Flight Acceptance Temperature (F/A) Limits During Flight:

	Epner Technology Diffuse Gold	Surface Optics Diffuse Gold
F/A: OS > 35 °C	0.2 %	0.0 %
AFT: OS > 30 °C	3.6 %	0.1 %
AFT: OS < -45 °C	0.0 %	14.4 %
F/A: OS < -50 °C	0.0 %	1.7%



Monte Carlo Temperature Study



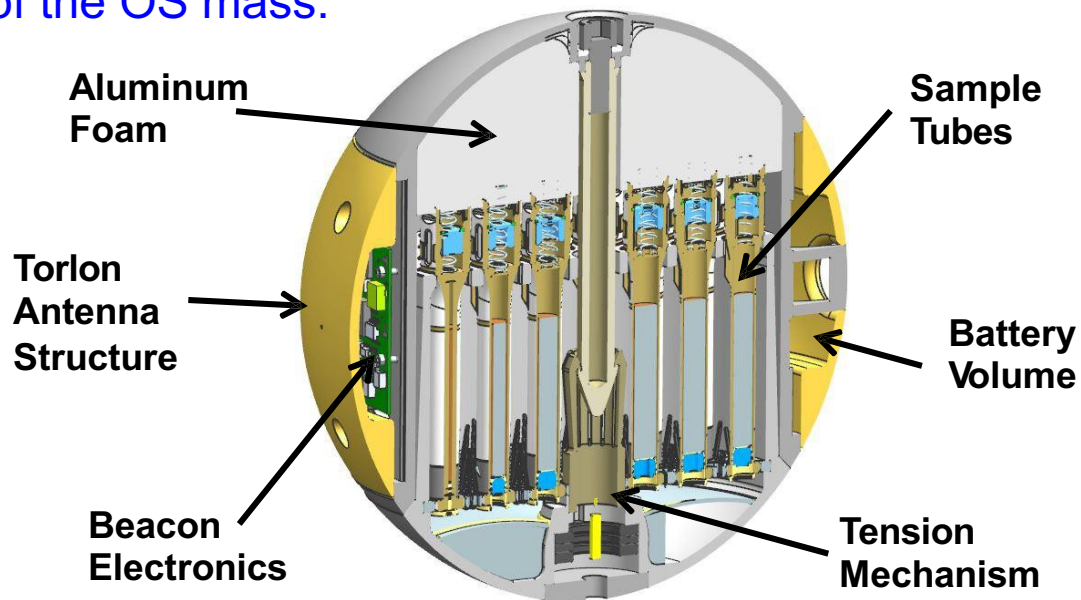
Results assume OS is:

- 85% Diffuse Gold
- 15% Black Paint



Transient Model

- All results shown so far were for the [OS Average Orbital Temperatures](#).
- However, the OS temperature would vary during orbit due to eclipse.
 - 1 node models show that a [12 Kg](#) OS will only vary by $\sim \pm 1$ C.
 - 1 node models show that a [1.4 Kg](#) OS will vary by $\sim \pm 10$ C.
- As a result, [sensitive components](#) like the battery, electronics, and sample tubes [should be buried inside the OS and well coupled to the bulk of the OS mass](#):



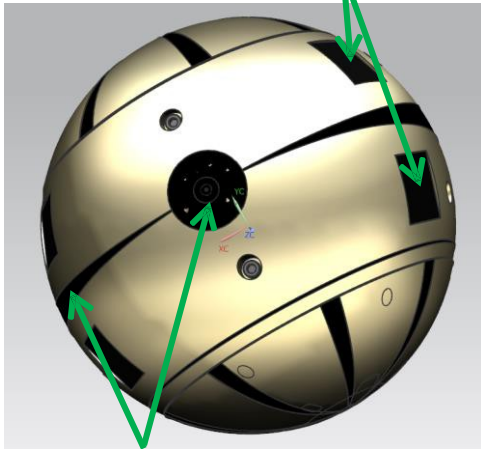
OS with Beacon Conceptual Design Cross Section



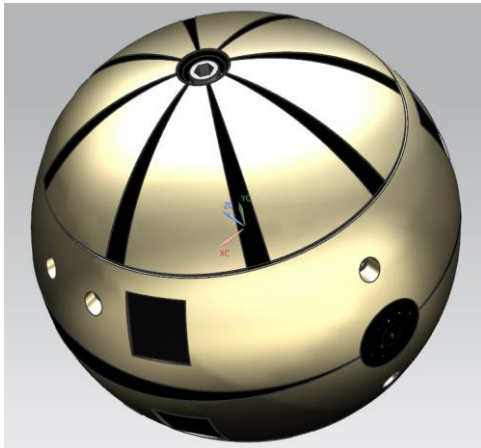
OS with Beacon Conceptual Design

Mars Mission Formulation

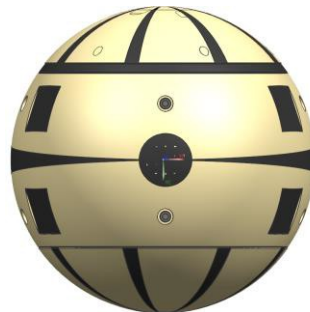
Solar Arrays



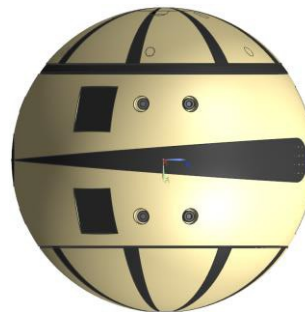
Slot Antenna



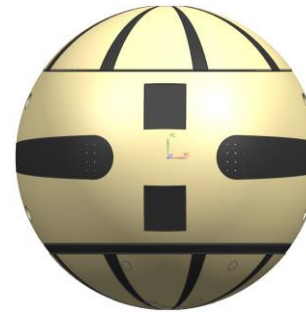
- If the OS is outfitted with a beacon, it would likely also have **solar arrays to recharge the batteries** and extend the beacon lifetime.
 - Concept is **6 solar arrays** with 120° azimuthal spacing and $\pm 20^\circ$ elevation angles.
- A **slot antenna** is likely superior to a patch antenna:
 - Slot antennas allow a larger fraction of the OS to be diffuse gold coated.
 - Slot antennas allow more flexible placement of solar arrays without RF interference.



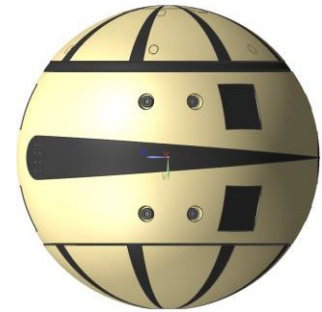
Back



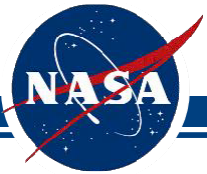
Left



Front

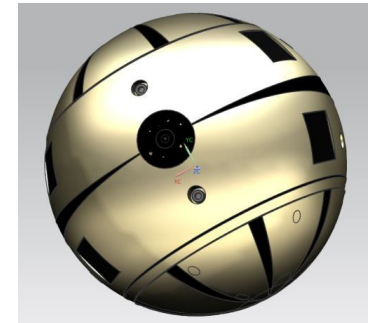
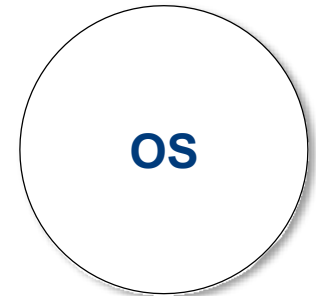


Right



Conclusions

- It is feasible to passively control temperatures on an Orbiting Sample as a part of a potential Mars Sample Return mission.
 - Very simple without a Beacon.
 - Temperatures can be cold biased using white paint, with black features as needed for aid in tracking and orientation.
 - The solar reflectivity of a white painted OS is > 0.6 .
 - Feasible, but more challenging, with a Beacon.
 - Temperatures can be controlled using a combination of $\sim 85\%$ diffuse gold and $\sim 15\%$ black paint.
 - Multiple vendors have the capability to produce diffuse gold that can provide appropriate thermoptical properties.
 - Sensitive components like the battery, electronics, and sample tubes should be buried inside the OS and well coupled to the bulk of the OS mass.
 - The solar reflectivity of a diffuse gold / black painted OS is > 0.58 .





Acknowledgements

This work would not have been possible without the support of the Advanced Development Team (ADT) including, but not limited to, Dave Rosing, Scott Perino, Darren Cooper, Chad Truitt, Joel Schwartz, Vahraz Jamnejad, Eric Archer, Marshall Smart, and Tom Komarek.



References

1. Witze, A., "NASA plans Mars sample-return rover," Nature News, 13 May 2014.
2. Perino, S., et al., "The Evolution of an Orbiting Sample Container for Potential Mars Sample Return," IEEE Aerospace Conference, Big Sky, MT, March 4-11, 2017.
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